Brazilian Defense Plan Against Extreme Contingencies

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Abstract: *This paper presents some of the short-term measures developed from the studies following the blackout in the Brazilian South/Southeast/Center-West power system in March 11th 1999. The concept of Security Zones and Network Security Matrix is introduced. A new PLC-based SPS was designed to create controllability zones. This new scheme was named Security Control and is triggered by network topological changes. The Security Control is fast acting, with clearing times around 200 ms. A typical Security Controller logic is presented, showing its benefits for the Brazilian interconnected power system.*

Keywords: Extreme Contingencies, Special Protection Schemes, Network Security Control, Programmable Logic Controller, Security Zone, Angle Stability Control, Voltage Collapse

INTRODUCTION

The March 11th blackout caused the loss of 25 GW of load and was the most severe of the Brazilian electric system history. The Minister for Energy, concerned with the security of the Brazilian power system, instructed ELETROBRÁS, the holding company of the Brazilian Federal utilities, to coordinate studies and define actions to reduce the probability and severity of large disturbances and associated blackouts.

ELETROBRÁS rapidly formed seven task forces, involving engineers from the various utilities, to define measures for the improvement of the reliability and security of the Brazilian South/Southeast/Center-West power system. Among the short-term measures, it is worth highlighting the commissioning of various new special protection schemes, involving mainly generator tripping, in order to minimize the impact of bus faults (or line faults with breaker failure) in critical substations.

The medium and long-term measures comprise several improvements in the system to effectively enlarge the operational margins, which have been critical due to the unanticipated load growth in recent years. Reinforcements in both generation and transmission assets are proposed. Other actions are also foreseen, such as the addition and modernization of equipment, accompanied by the installation of a network of dynamic system monitors.

This paper describes the work carried out by the Joint Working Group responsible for improving the security of the Brazilian Interconnected Power System. The concepts of Network Security Matrix and Security Zones are introduced. A PLC-based SPS triggered by network topological changes is presented. The concepts involved in the design of SPSs are described together with one typical SPS application.

THE BRAZILIAN POWER SYSTEM

The Brazilian electric power system presents some unique characteristics. It has a predominantly hydro generation (around 94%) with large amounts of energy being transferred from remote sites to the load centers, through long distance power corridors operated in EHV. The total installed capacity is 65 GW and the Itaipu power plant itself is responsible for more than 18% of the total energy production in the country. There are frequent operating conditions that involve heavy energy transfers, even during light load, due to hydroelectric coordination for optimal water usage.

System planning is currently based on the (n-1) criterion where a temporary fault in a single generation or transmission element should not cause supply interruption or violations in system operating limits. The Brazilian system has been continuously experiencing a high load growth, around 5% per year. This fact, coupled with recent economic constraints, caused the system to operate closer to stability limits, thus increasing the probability of system-wide effects following major disturbances.

THE BLACKOUT OF MARCH 11th 1999

The initiating event of the March 11th 1999 blackout was a phase-to-ground fault at the Bauru 440 kV bus, which caused the opening of five incoming 440 kV lines. The power system survived the first event, but then collapsed because of a shortcoming of backup relaying. The subsequent outages of several power plants in the São Paulo area, followed by the loss of both the HVDC and the 750 kV AC links from Itaipu, resulted in a complete system break up and a load loss of 24,731 MW. This disturbance affected as much as 75 million people, for as long as four hours. Several natural islands remained in operation, totaling 10,000 MW.

In the South region, the total load restoration was performed in 49 minutes. In the federal states of Minas Gerais, Goiás, Federal District, Mato Grosso and Tocantins restoration took 30 minutes. There was a complete blackout in the federal states of São Paulo, Rio de Janeiro, Espírito Santo and Mato Grosso do Sul. The restoration process was much slower (up to 4 hours) in these four states, due to unforeseen difficulties and some equipment damage.

THE ACTIVITIES OF THE BLACKOUT JOINT WORKING GROUP

The March 11th 1999 blackout was the most severe disturbance experienced by the Brazilian power industry. ELETROBRÁS, under the instruction of the Ministry of Energy, convened a Joint Working Group involving CEPEL (the Brazilian Electric Power Research Center), ONS (the Brazilian ISO), and most of the utilities, to study the event and propose measures to improve the overall system security. The recommendations of the study include short, medium and long-term measures to reduce the probability of system-wide breakups following multiple contingencies.

The general guidelines established by the Joint Working Group were as follows:

- Analysis of substation layouts and proposal for most cost-effective changes and equipment additions;
- Assessment of existing Special Protection Schemes (SPS) and improvements;
- Implementation of fast acting SPSs, PLC-based, with direct detection of extreme contingencies;
- Reports by international experts;
- Moderate-cost reinforcements that enhance security.

The Joint WG activities were then organized in a number of Task Forces:

Task Force 1
Scope: Identification of the critical EHV substations, where single faults may lead to multiple outages. The studies have taken into account the detailed bus arrangements and associated protections of every substation in the system.
Objectives: A major list of critical substations ranked according to their probability of causing multiple contingencies and large impact to the system. This substation ranking information was later used by the Task Forces 2, 5, 6 and 7.

Task Force 2
Scope: Based on the results of TF 1, a deeper analysis of the critical substations was made to determine effective modifications to the local protection and bus arrangements (e.g.: changes in line bays, local protection philosophy, bus design, etc.) to improve substation performance.
Objectives: A set of recommendations involving changes in the bus arrangement, equipment additions and protection of the main substations.

Task Force 3
Scope: Description of the defense measures against extreme contingencies in USA, Canada and France. Study of other large disturbances, their causes, required time to perform analysis, restoration times and remedial actions taken after such events.
Objectives: Technical Reports used for guiding the work of the Joint Working Group, prepared by international experts.

Task Force 4
Scope: Enhancements to the supervisory control systems in Brazil.
Objectives: Design specification for synchronized RTUs in the interconnected system, wide-area dynamic system monitoring network (including long duration recorders), modern operator training simulators, specification of the basic Programmable Logic Controllers (PLC) to be used in the implementation of the SPSs.

Task Force 5
Scope: Studies to determine the effectiveness of the existing SPSs.
Objectives: Recommendations for retuning the existing SPSs, when needed.

Task Force 6
Scope: Addition of new PLC-based SPSs to augment the protective cover against extreme contingencies.
Objectives: Determine the locations and develop the basic functions for the new SPSs.

Task Force 7
Scope: Identification of the planned system reinforcements that minimize the impact of extreme contingencies.
Objectives: Ranking list of system reinforcements.

SECURITY ZONES AND THE NETWORK SECURITY MATRIX

The Brazilian South/Southeast/Center-West power system was divided into five Security Zones (SZ). A Security Zone is an electric region or a major generation-transmission system protected by a network of PLC-based SPSs. The Security Zones for the South/Southeast/Center-West system are shown in Figure 1. Note that SZ3 comprises three sub-zones.

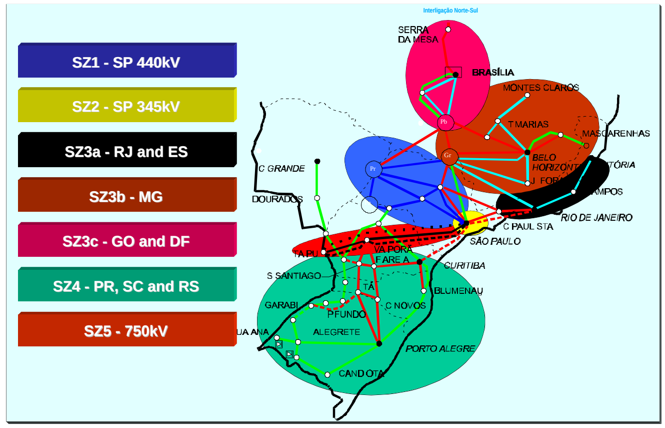

Figure 1: Security Zones

All major EHV substations were then classified according to two factors. The first factor is the impact level to system security of a bus fault at the substation. The second factor is the intrinsic reliability level of the substation (layout, protection, major incoming lines and their characteristics, i.e., double-circuit tower, etc.). Each factor is ranked in three grades as explained below and depicted in Figure 2:

Impact to the EHV Network Security

P1 – Substations where faults lead to extreme contingencies;
P2 – Substations where faults cause severe impact to the system, but not extreme contingencies;
P3 – Substations where faults cause a minor impact to the system.

Intrinsic Reliability Level of Substation

S1 – Substations presenting high risk of outages;
S2 – Substations presenting some risk of outages;
S3 – Substations whose layout and protection characteristics make them secure, presenting very low risk of outages.

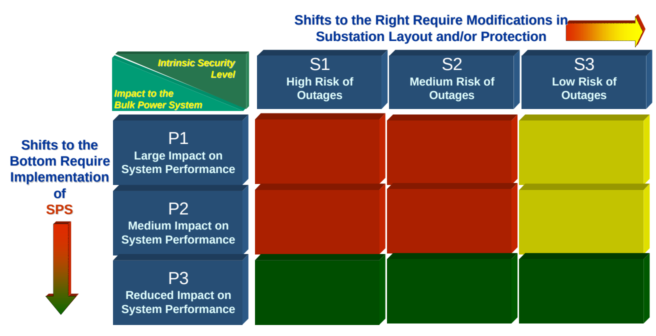

Figure 2: The Network Security Matrix Concept

The various EHV substations, classified according to the previous two factors, were then adequately included into the color-coded Network Security Matrix (NSM). Figure 3 depicts the NSM relative to March 1999, assuming a complete substation outage following a bus fault. This severe fault criterion was initially adopted (Task Force 1 report) to speed up the critical bus

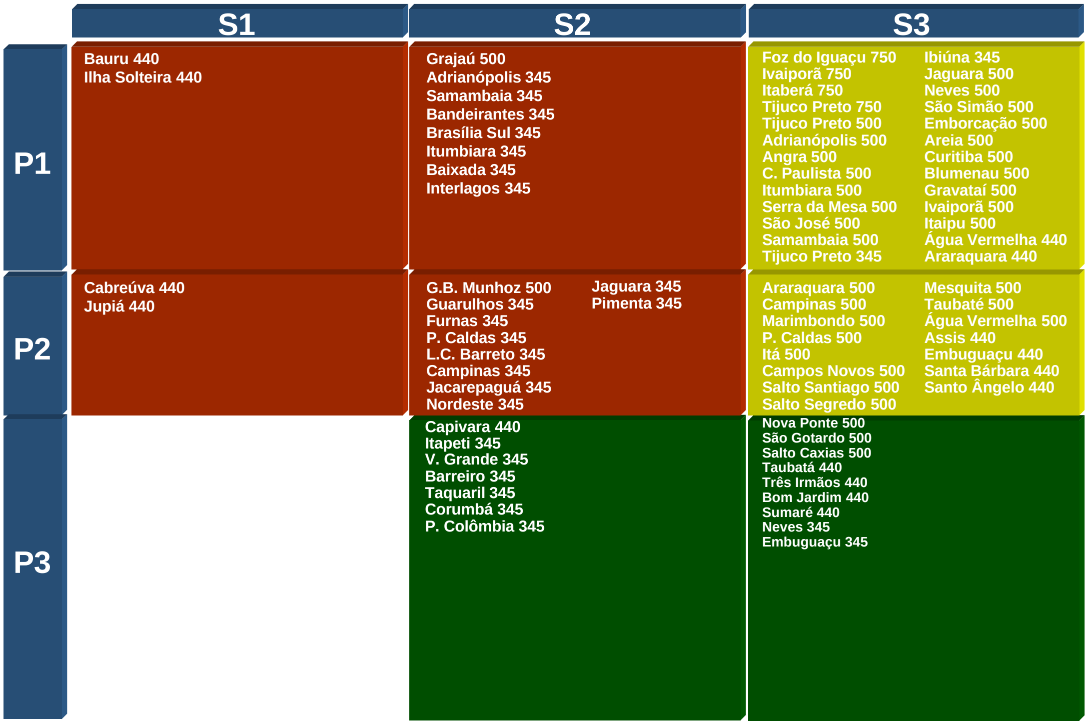

Figure 3: NSM Status in March 1999

screening process. The red, yellow and green colors in the NSM stand for high risk, medium risk and low risk substations. The 22 critical substations located in the red section were given priority in the detailed stability studies, properly considering bus arrangement and protection aspects. Note that Bauru 440kV substation, where the March 11^{th} 1999 blackout was initiated, is classified as a high risk/large impact facility.

The main objective of task forces 2, 5 and 6 was to develop remedial measures (improved bus protection schemes, substation layout changes, minor equipment additions and new special protection schemes) to reduce system risk and, consequently, move the critical substations away from the red zone. Figure 2 shows how the remedial measures allow displacing (both horizontal and vertically) the substations to more secure zones (yellow and green) in the NSM.

Task Forces 5 and 6 have revised the adequacy of the existing SPSs and designed new PLC-based SPSs to cope with extreme contingencies, such as EHV bus faults. Several SPSs have already been designed and the Brasilia Sul PLC-based SPS at SZ3c is under commercial operation since October 2000. The Adrianopolis 345 kV and Jaguara 345 kV new SPSs, located in sub-zones SZ3a and SZ3b are currently under assisted operation. For these three sub-zones, a total of 37 PLCs were implemented at key substations of the Brazilian interconnected power system. Figure 4 shows the standard PLC cabinet adopted in this project.

The work already produced by Task Forces 2, 5 and 6 yielded a significant increase of the system security for most of the critical EHV substations.

Figure 5 depicts the evolving level of system risk associated with major bus faults at the Bauru 440 kV substation. The risk reduction is achieved by the implementation of the Joint WG recommendations. The upper region (in red color) in Figure 5 corresponds to the highest level of risk, while the lowest risk region is located at the bottom (in green color).

Figure 4: PLC Cabinet – Brazilian Defense Plan

The NSM has a continuously evolving nature, being a function of the security measures implemented, such as: changes in substation layouts, minor equipment additions, transposition of incoming transmission lines, improved local protection schemes, introduction of emergency stability controls and fast action PLC-based SPS.

The expected status of the NSM in May 2001 is shown in Figure 6. It should be noticed that the substations previously located in the highest risk region (in red color) of the NSM have been shifted away through one or more remedial control actions. The actions proposed by the Joint WG have improved system security, successfully removing the 22 critical substations from the red section of the NSM.

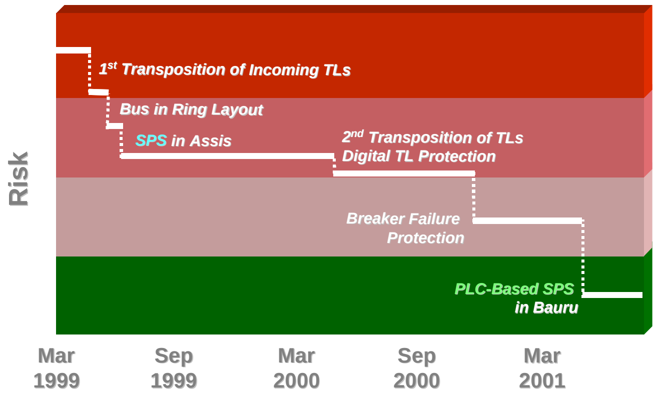

Figure 5: Reduction in Risk Level for Bauru 440kV Substation

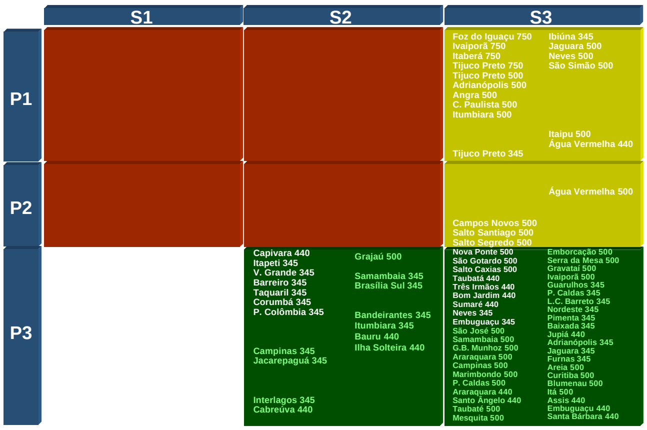

Figure 6: Expected Status of the NSM in May 2001

SPECIAL PROTECTION SCHEMES FOR SECURITY CONTROL

This section presents the PLC-based SPS solution adopted as one of the short-term measures to improve security of the Brazilian interconnected power system. This fast acting SPS, named Security Control, is triggered by network topological changes with clearing times around 200 ms.

The Security Control is highly dependent on an effective communication network. The information exchange within a security zone and among neighboring zones must be fast, organized and reliable to ensure the proper operation of the SPS logic.

Figure 7 depicts the geographical distribution of the various PLCs in Security Zone 3a (Rio de Janeiro and Espírito Santo states) associated with the Adrianópolis 345kV Security Control.

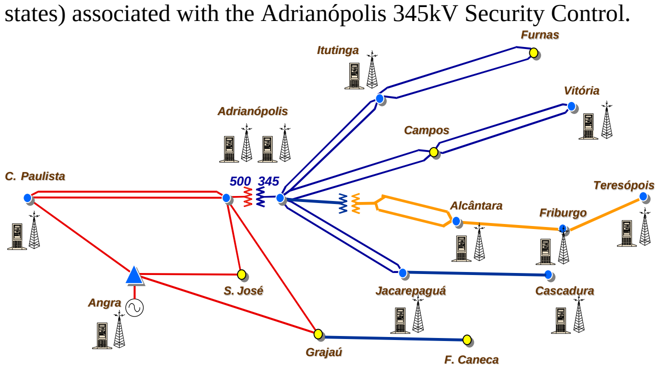

Figure 7: Locations of the Various PLCs Associated with the Adrianópolis Security Control – Security Zone 3a

Communication Structure

The communication network structure renders better performance to the SPS, considering the security zone concept and the wide geographic regions to be covered. This structure is made up of three hierarchical layers. In the basic level, the information exchange is performed exclusively within the security zones, depicting the so-called *intra-zone communication*. Each of the PLCs in a zone acquires system data (local voltages and power flows, status of switching devices, etc) and receives control orders (generator tripping, load shedding) in a master-slave relationship. The Master PLC is unique in the zone and concentrates the data sent by the slaves, runs the Security Control logics and transmits orders to the slave PLCs.

Figure 8 shows the *intra-zone communication* in Security Zone 3a. It is worth noting that the slaves themselves do not communicate with each other. Information that must be transferred between any two substations must flow through the Master PLC and this dramatically reduces the number of communication channels. Several different types of communication media are being used on the Brazilian Defense Plan, including a network of fiber optics, microwave channels, local networks provided by telecommunication utilities and, under special circumstances, satellite channels.

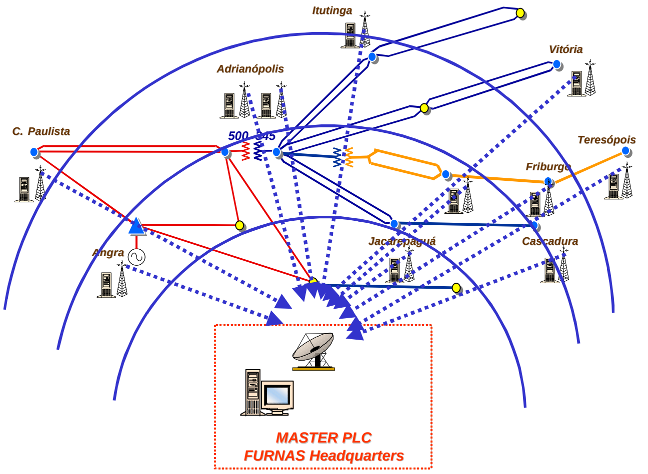

Figure 8: Intra-Zone Communication

It is important to mention that the communication link between any slave PLC and the Master station is duplicated, preferably with different communication media to increase system reliability. The Master station hardware is also duplicated, running on a hot-stand-by configuration.

The Master PLCs are the key elements in the communication structure. They are responsible for the main processing in the PLC-based Security Control, and are the depositary of the security zones' real-time information. This includes GPS synchronized sequence of events during a major disturbance. Therefore, whenever the logic of a Security Control that is concerned with a specific security zone requires any information from a neighboring zone, this is done through their Master PLCs. They are, hence, the gateways to allow the information exchange among security zones in a higher level of the communication structure, creating a controllability network. An example of this *inter-zone communication* level is illustrated in Figure 9.

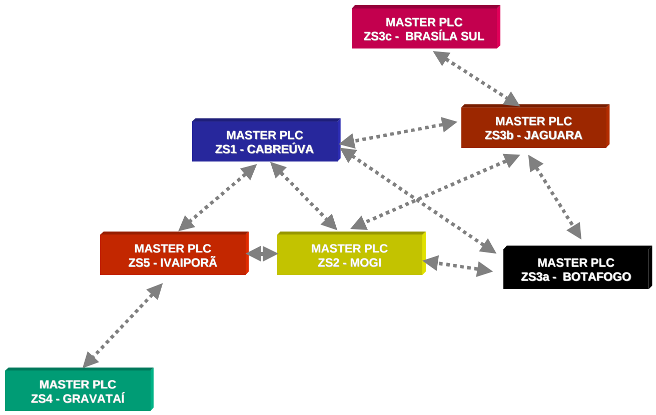

Figure 9: Inter-Zone Communication

The highest level in the communication structure refers to the information exchange with the National Supervisory Center (CNOS). As depicted in Figure 10, the Master PLCs, and hence the security zones, are permanently supervised by the CNOS, which may block/unblock the operation of SPSs by transmitting halt commands whenever necessary.

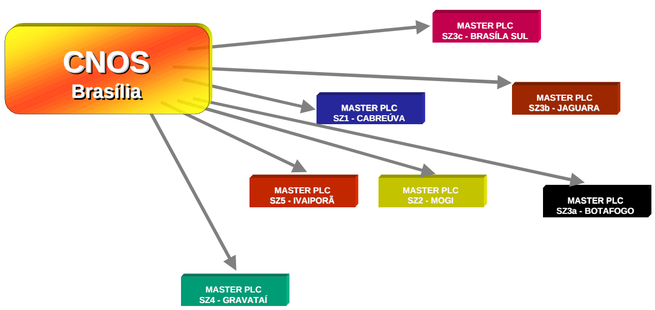

Figure 10: Communication with the National Supervisory Center

Example of a PLC-Based Security Control

One of the first Security Controllers to have the design of its basic logic completed is associated with the Jaguara 345 kV substation. Figure 11 shows the 500/345 kV grid of the Minas Gerais federal state. The studies performed in Task Force 1 indicated that a bus fault at the 345 kV section of Jaguara, followed by the 500/345 kV bus tie-breaker failure, is an extreme contingency.

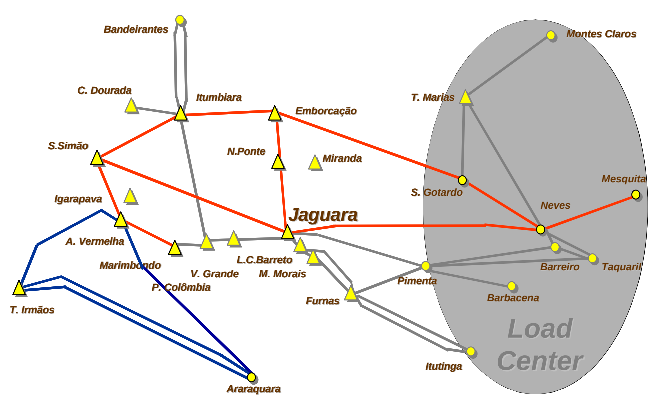

Figure 11: Minas Gerais 500/345kV Grid

Such contingency, although having a low probability, may lead to multiple outages and voltage collapse in the load center (see Figure 11). As a result of the failure in the tie-breaker, the 345 kV bus fault clearing would rely only on the remote protection of the incoming 345 kV and 500 kV lines. This would shut down the complete Jaguara substation. The immediate consequences of this critical transmission outage are a power flow increase in the corridor Emborcação – São Gotardo – Neves and a huge voltage depression in the load center, as shown in Figures 12 and 13. In a few seconds, the line protection would trip out the São Gotardo – Neves circuit. A voltage collapse would then occur.

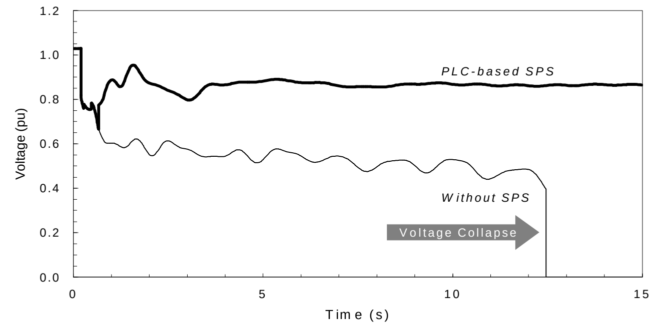

Figure 12: Neves 138 kV Bus Voltage

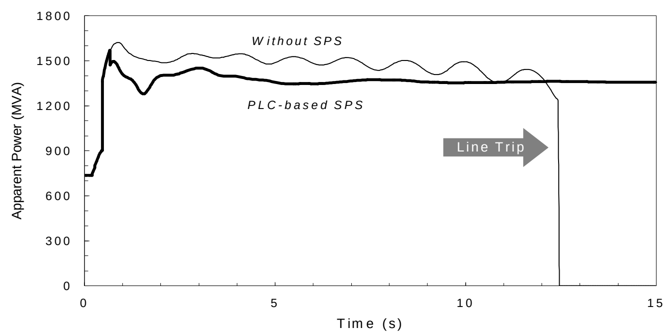

Figure 13: São Gotardo – Neves 500 kV Line Flow

The Jaguara Security Control was designed to reduce the impact of this extreme contingency, as well as of several other contingencies that may result from the loss of equipment in that region. The basic information used to program such logic is obtained from thousands of transient stability runs, for different load scenarios and possible network configurations. In fact, whenever a new equipment is introduced in a Security Zone, new transient stability evaluations must be carried out to guarantee that every possible case is covered by the designed logic. It is fair to say that the intelligence of the Security Controller will evolve over the years, as new studies are performed and fedback into the controller.

Figure 14 shows the basic PLC arrangement for the 500/345 kV grid of the Minas Gerais state. The Master station is located at the Jaguara substation and the slave PLCs are permanently monitoring the network topology to identify any probable bus fault or tie-breaker failure event. Whenever a fault is detected, partial logics are processed on the slave PLCs, and fedback with all the necessary additional information to the Master station that ultimately processes the Security Control logic. In this specific case, the Master PLC will order partial generator tripping at São Simão and Emborcação power plants and a load shedding around the Neves load area, as depicted in Figure 15. Figures 12 and 13 show that the Security Controller successfully avoids the system voltage collapse after an extreme contingency.

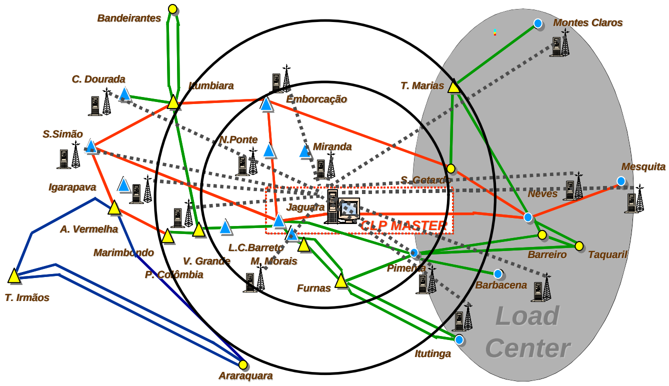

Figure 14: Basic PLC Arrangement for the Minas Gerais 500/345kV Grid

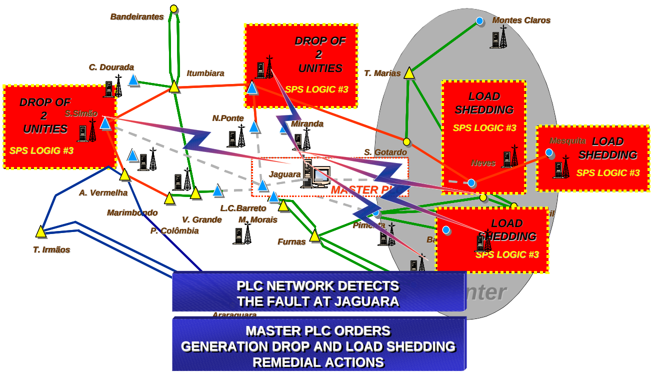

Figure 15: Generator Tripping and Load Shedding Ordered by the Jaguara Security Controller

CONCLUSIONS

The main purpose of this paper was to present an overview of the Brazilian Defense Plan against extreme contingencies. This defense plan was triggered by the March 11th 1999 blackout that caused the loss of 25 GW of load and was the most severe of the Brazilian electric system history. This disturbance affected as much as 75 million people, for as long as four hours.

The Joint Working Group convened by ELETROBRÁS developed criteria to assess the potential risk of multiple outages initiated by faults in the substations of the main grid, and proposed a number of security measures to be implemented in the short, medium and long-term to reduce the probability of system-wide breakups.

The concepts of Network Security Matrix and Security Zones are introduced. The NSM is an interesting way to classify substations according to their impact on system dynamic performance and intrinsic security. A PLC-based SPS triggered by network topological changes is presented. The concepts involved in the design of this fast acting security controller are described and a typical result applied to the Brazilian power system is presented.

In the last six months, three Security Controllers were put into operation in the Brazilian grid, involving the implementation of PLCs at 37 substations. Several other new Security Controllers are to be implemented in the near future.

All the work carried out by the Joint Working Group is currently being extended to the Brazilian North/Northeast grid.

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BIOGRAPHIES

Xisto Vieira Filho (SM'96) received the B.Sc. (1966) from the Catholic University of Rio de Janeiro, Brazil and the M.Sc. (1970) from the Rensselaer Polytechnic Institute, all in electrical engineering. He is former Director of Planning and Operation of ELETROBRÁS, Secretary of Energy and currently General Director of CEPEL. Mr. Vieira Filho is a Senior Member of the IEEE Power Engineering Society and Chairman of the CIGRÉ Study Committee 38 - Power System Analysis Techniques.

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André Bianco (M'99) received the B.Sc. degree in 1990 from the Gama Filho University and the M.Sc. in 1994 from the Catholic University of Rio de Janeiro, both in electrical engineering. Mr. Bianco has been with CEPEL since 1988, being at the present time a Project Manager in the Power Systems Area. His main research interests are in the dynamic analysis of power systems including HVdc transmission and FACTS devices.